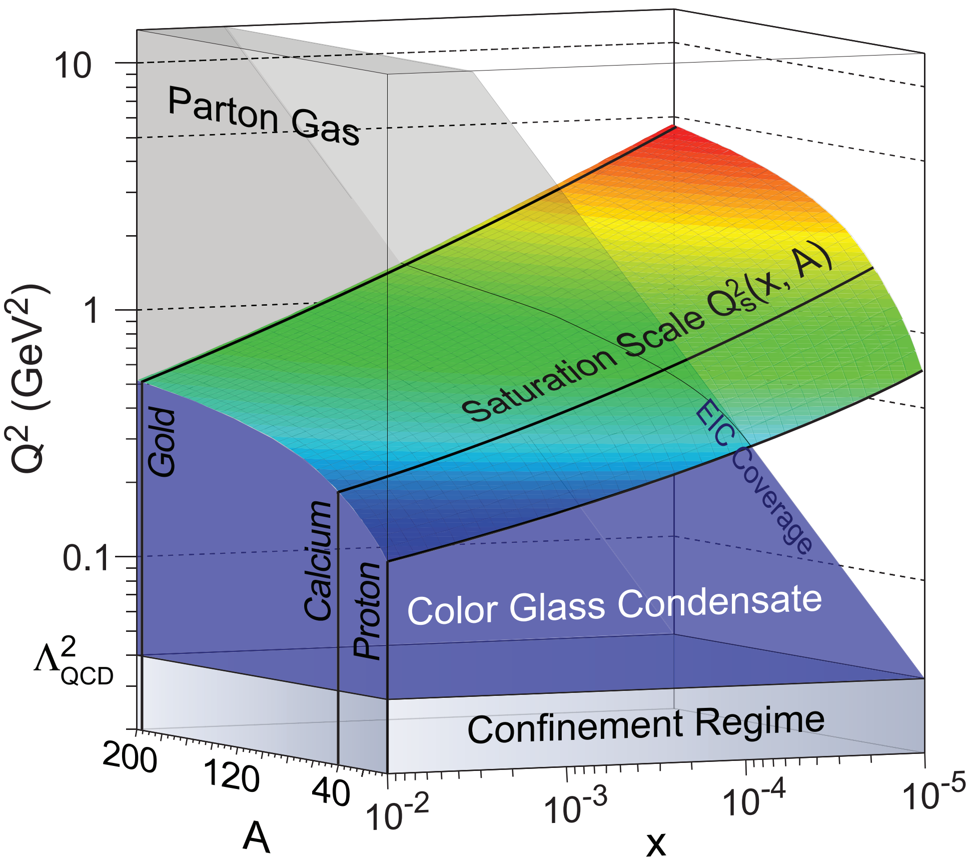
# Low-x Physics with Nuclei





*Thomas Ullrich*


EIC Advisory Committee Meeting

BNL, February 28, 2014

# Hadronic Wave Function at Low-x

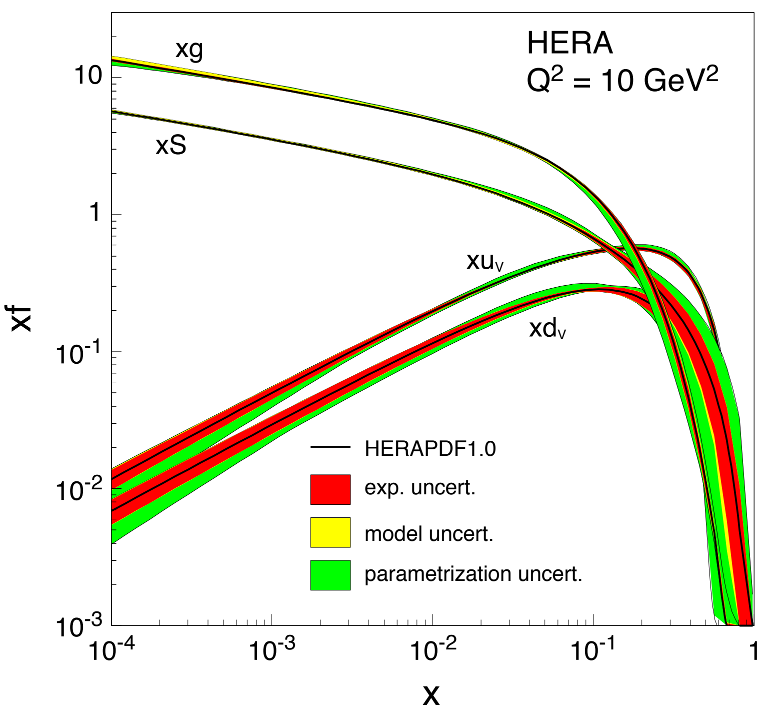
**Major challenge since discovery of QCD:**

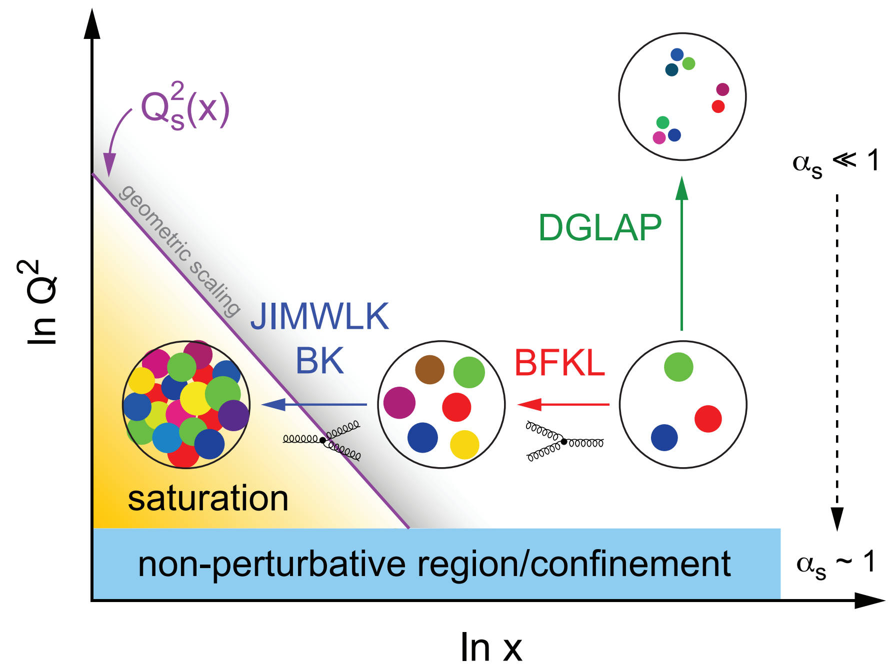
What is the structure of hadrons in the high-energy limit?

What are the dynamical degrees of freedom governing it?

From HERA:

- Glue dominates for $x < 0.1$




CGC emerged as best candidate to approximate QCD in saturation regime

- practical applicability
- phenomenological success

# Studying Saturation

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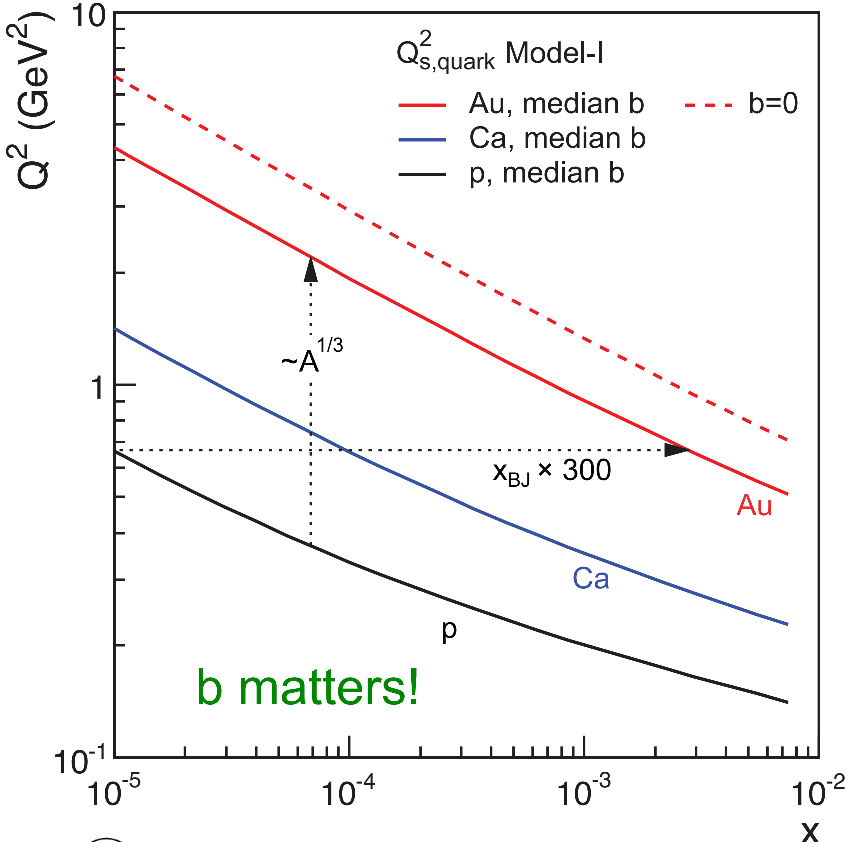
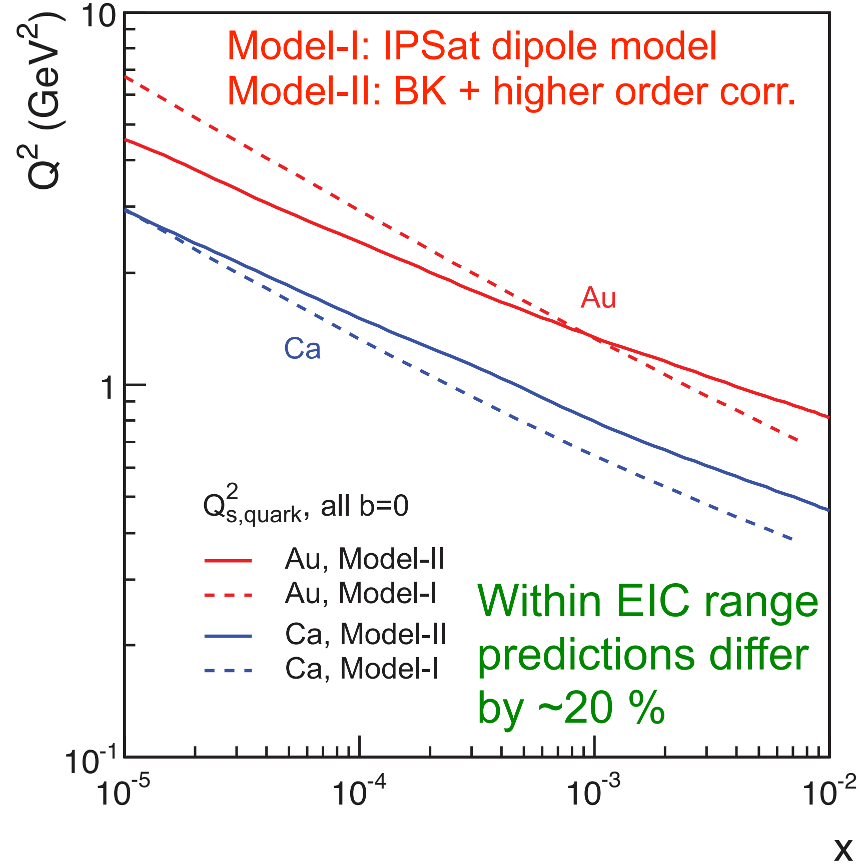
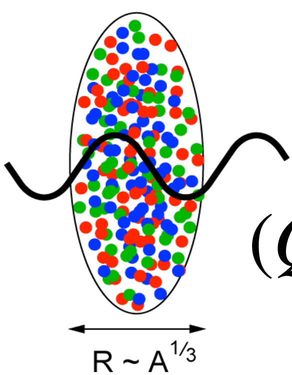
- Required: high energy to reach saturation regime $s \sim 1/x$
    - ep: need energies beyond HERA

# Nuclei as Amplifiers of Saturation Effects




$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of $Q_S$ with A ⇒
saturation regime reached at
significantly lower energy in nuclei

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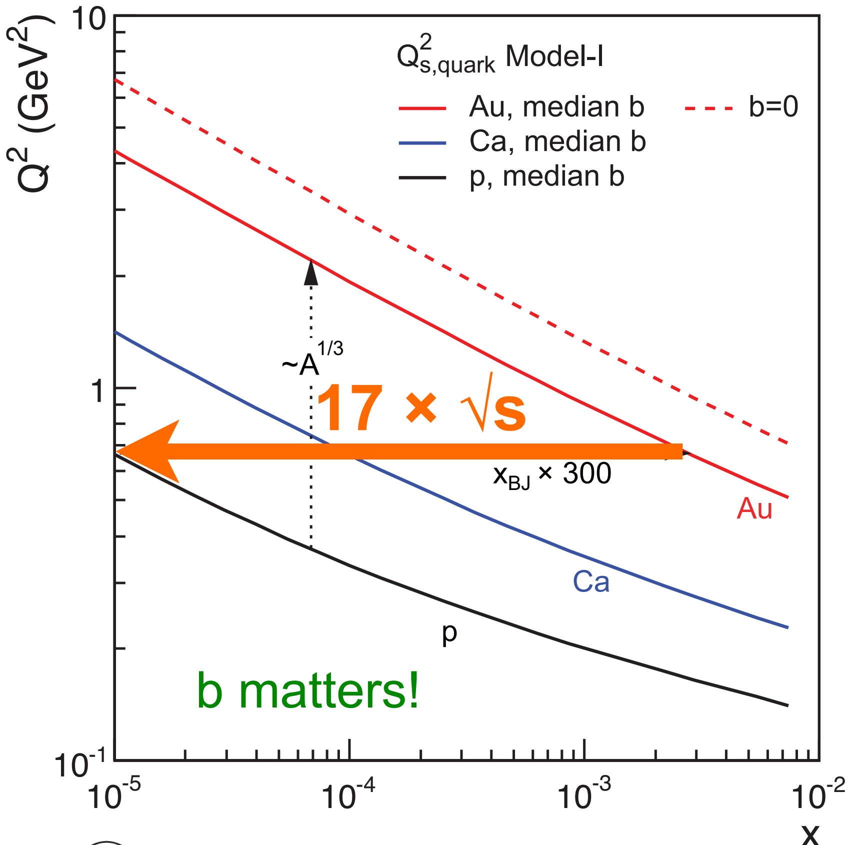


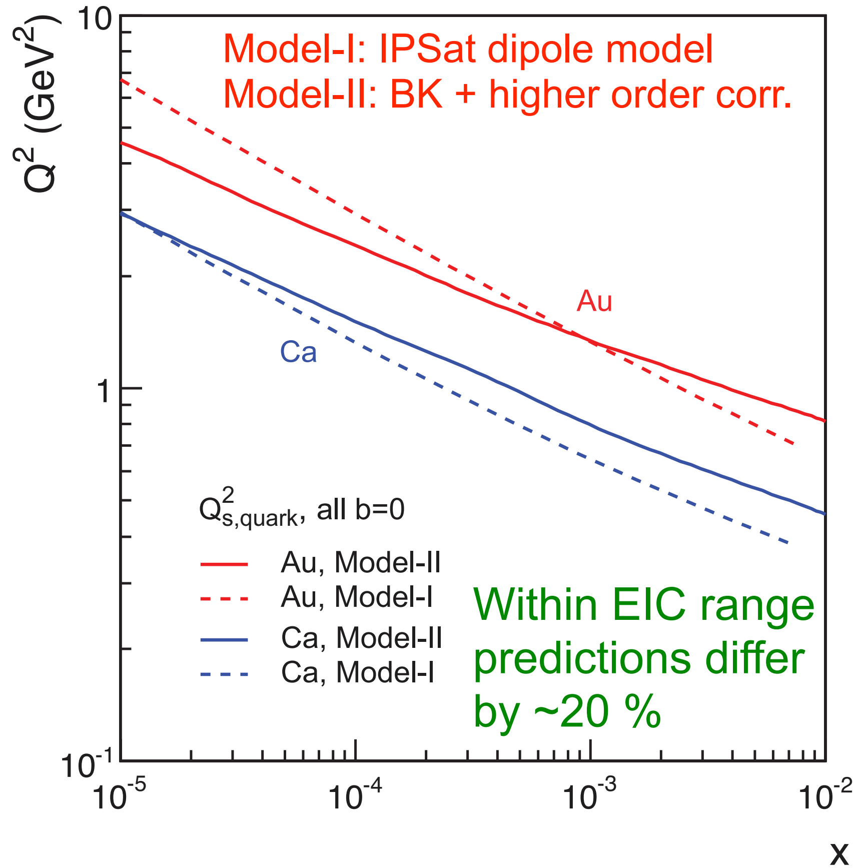


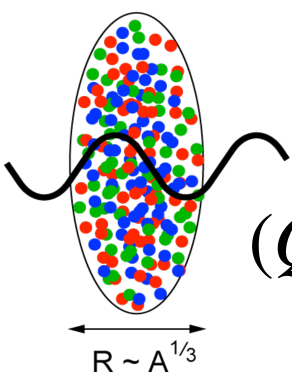


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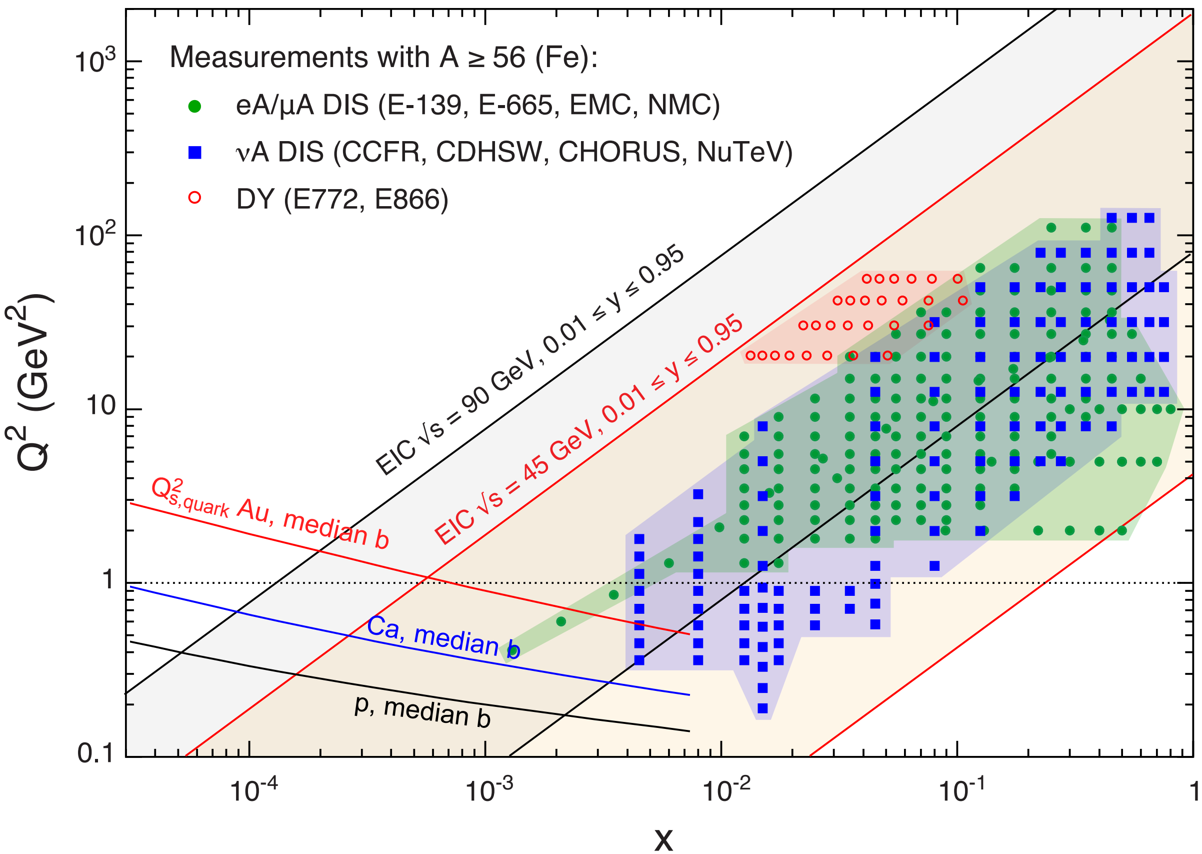
# The Pre-EIC Era



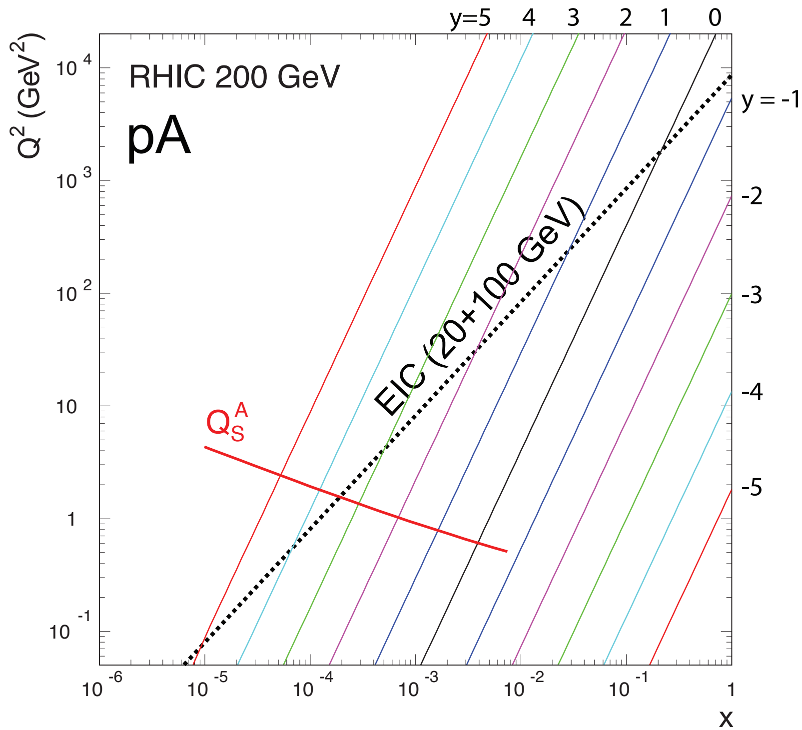

**Recall:**

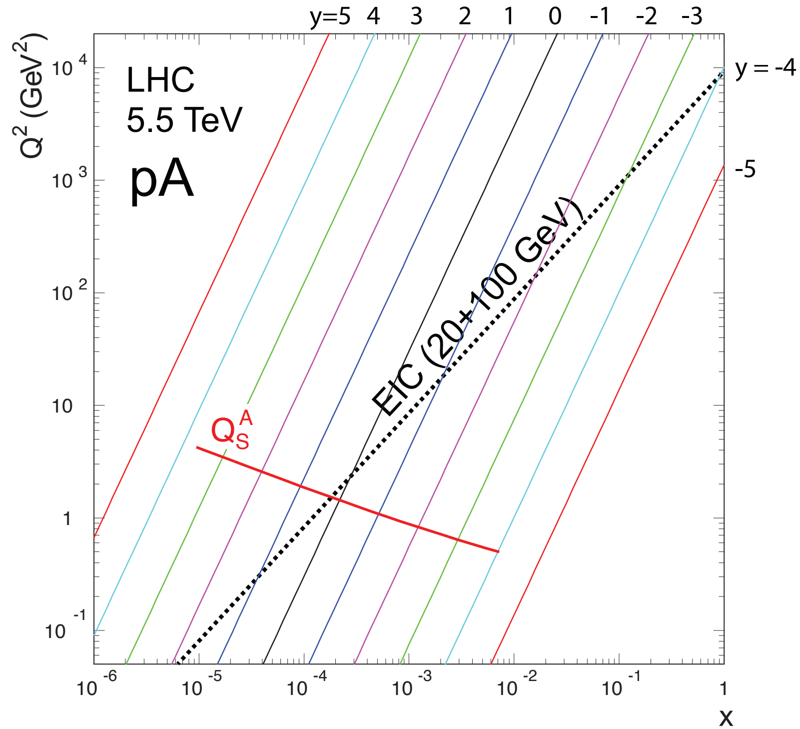
- 5+100 GeV ⇒ √s ~ 45 GeV
- 10+100 GeV ⇒ √s ~ 63 GeV
- 15+100 GeV ⇒ √s ~ 78 GeV
- 20+100 GeV ⇒ √s ~ 90 GeV

**Plot has more dimensions:**

- Statistics
  - typically low, large bins, no multi-differential studies
- Breadth of Measurements
  - mostly inclusive
  - often no comprehensive set of measurements (incl., SIDIS, excl., diffractive, ...)

# Pre-EIC: p+A at RHIC and LHC



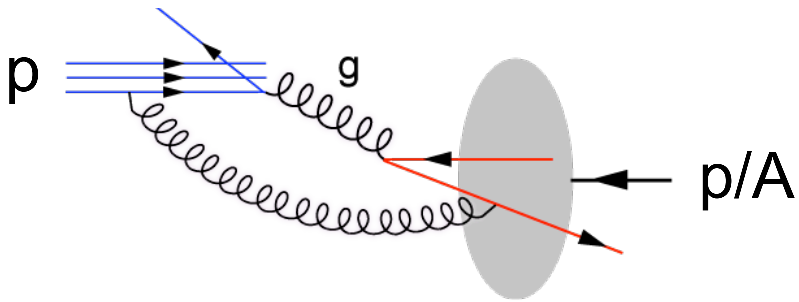




2→2 process
$$x_1 = \frac{Q}{\sqrt{s}}\, e^{y}$$
$$x_2 = \frac{Q}{\sqrt{s}}\, e^{-y}$$

**Studying Saturation:** RHIC: need overlap with forward physics (y~4)
LHC: low $p_T$: overlap with central region (y~0)

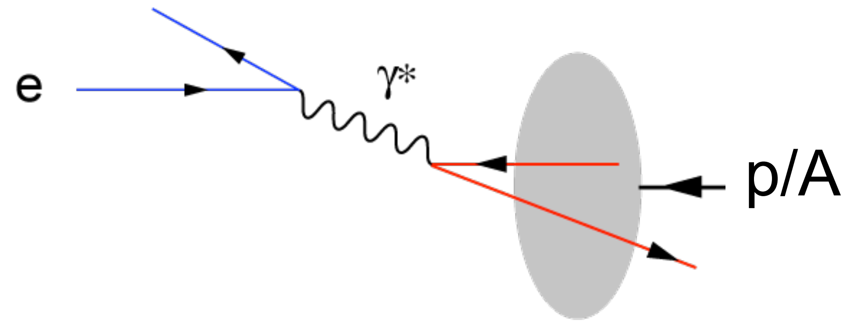
# Pre-EIC: p+A at RHIC and LHC

## Hadron-Hadron



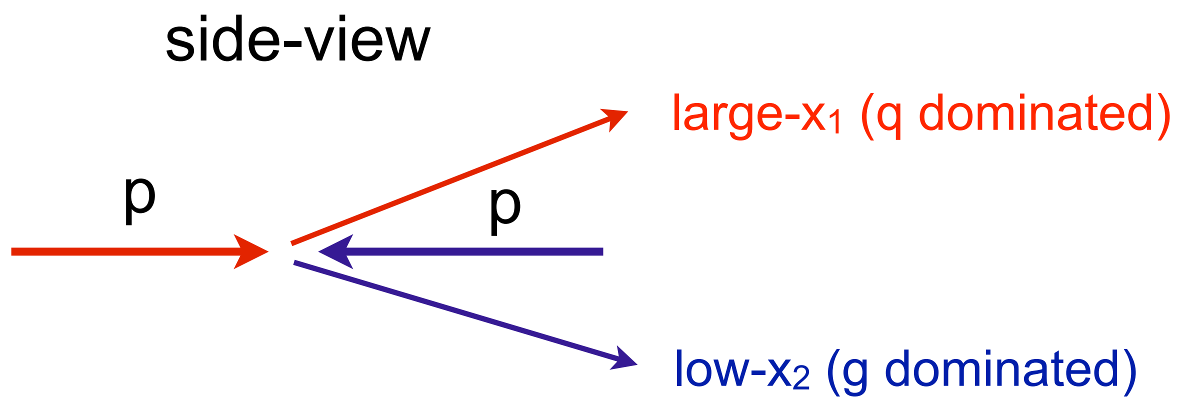

- Probe has structure as complex as the “target”
- More direct information on the response of a nuclear medium to gluon probe
- Soft color interactions before the collision can alter the nuclear wave function and destroy universality of parton properties (break factorization)

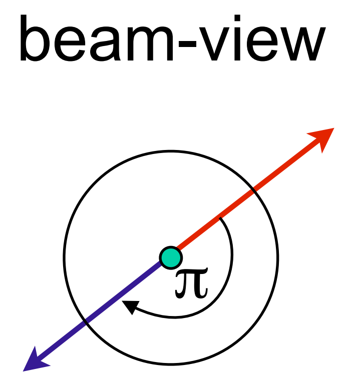
## Electron-Hadron (DIS)




- Point-like probe
- Dominated by single photon exchange ⇒ no direct color interaction ⇒ preserve the properties of partons in the nuclear wave function
- High precision & access to partonic kinematics
- Nuclei always “cold” nuclear matter (CNM)

# d+Au at RHIC: Forward-Forward Correlations



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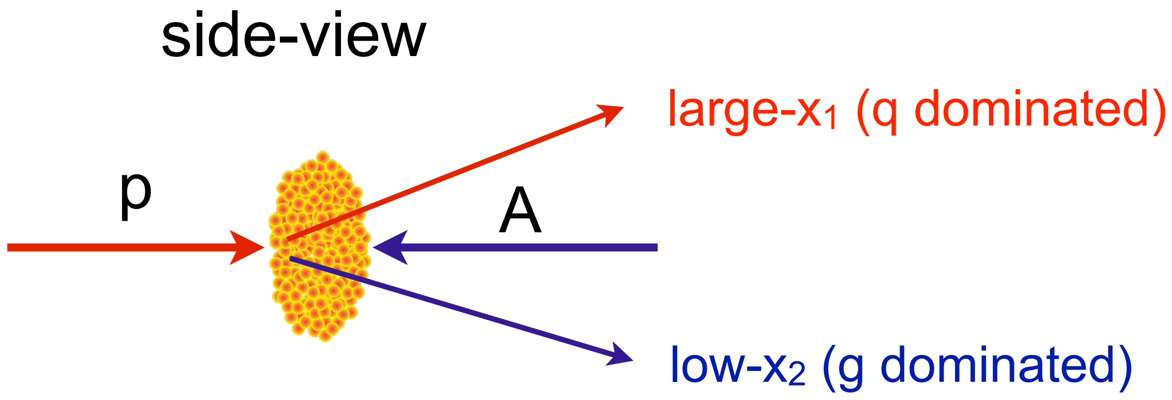
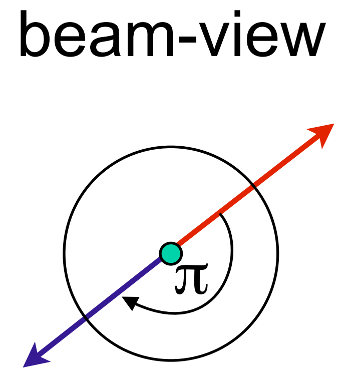
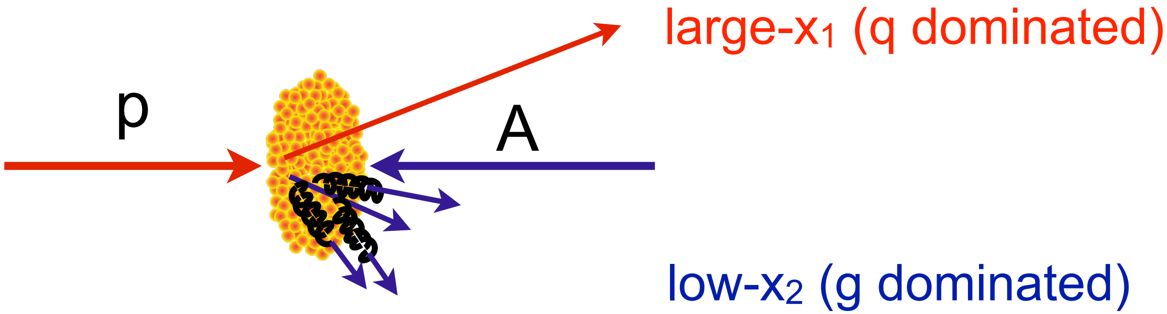


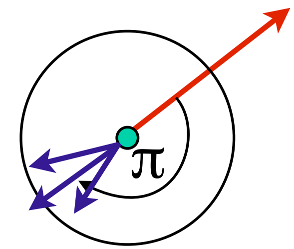



# d+Au at RHIC: Forward-Forward Correlations

side-view




beam-view



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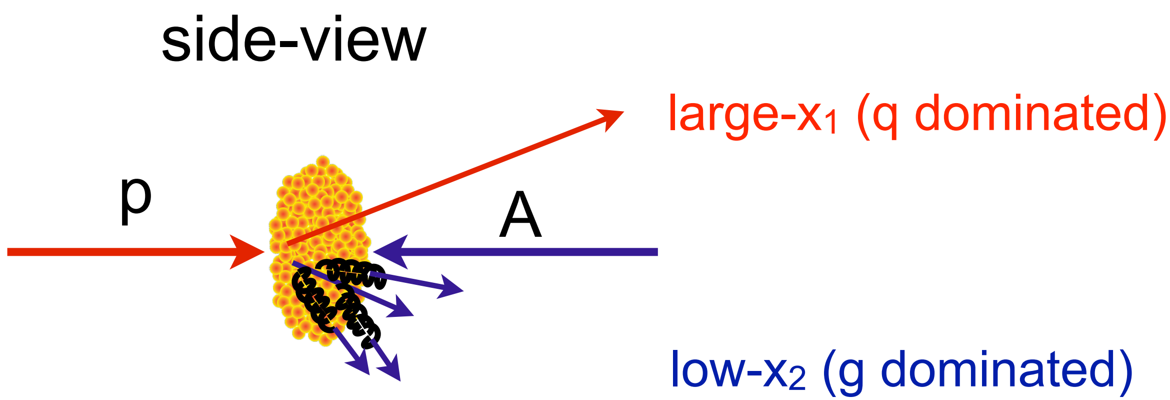


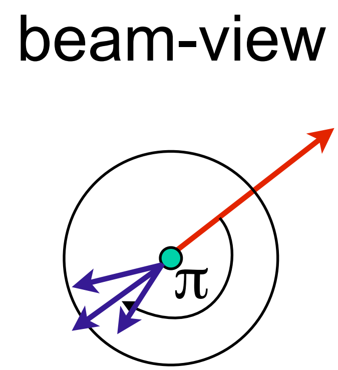


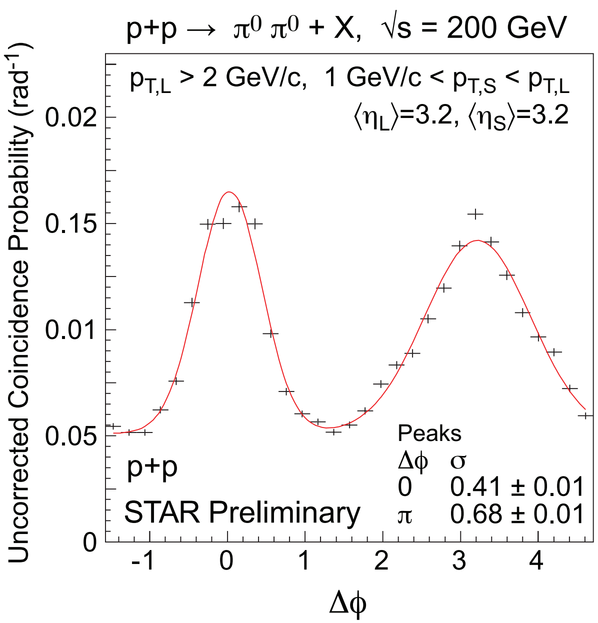


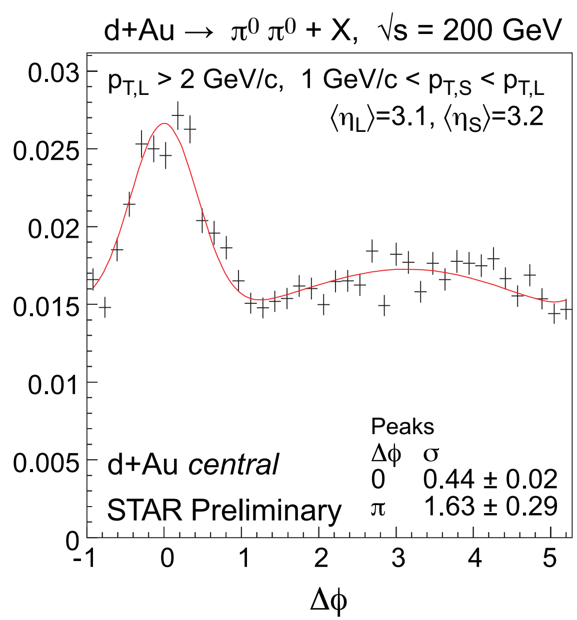


- Striking broadening in central dAu of away-side compared to pp and peripheral dAu
- Experimentally difficult due to large backgrounds
- No handle on parton kinematics $x$, $Q^2$

See also PHENIX, Phys. Rev. Lett. 107, 172301 (2011)

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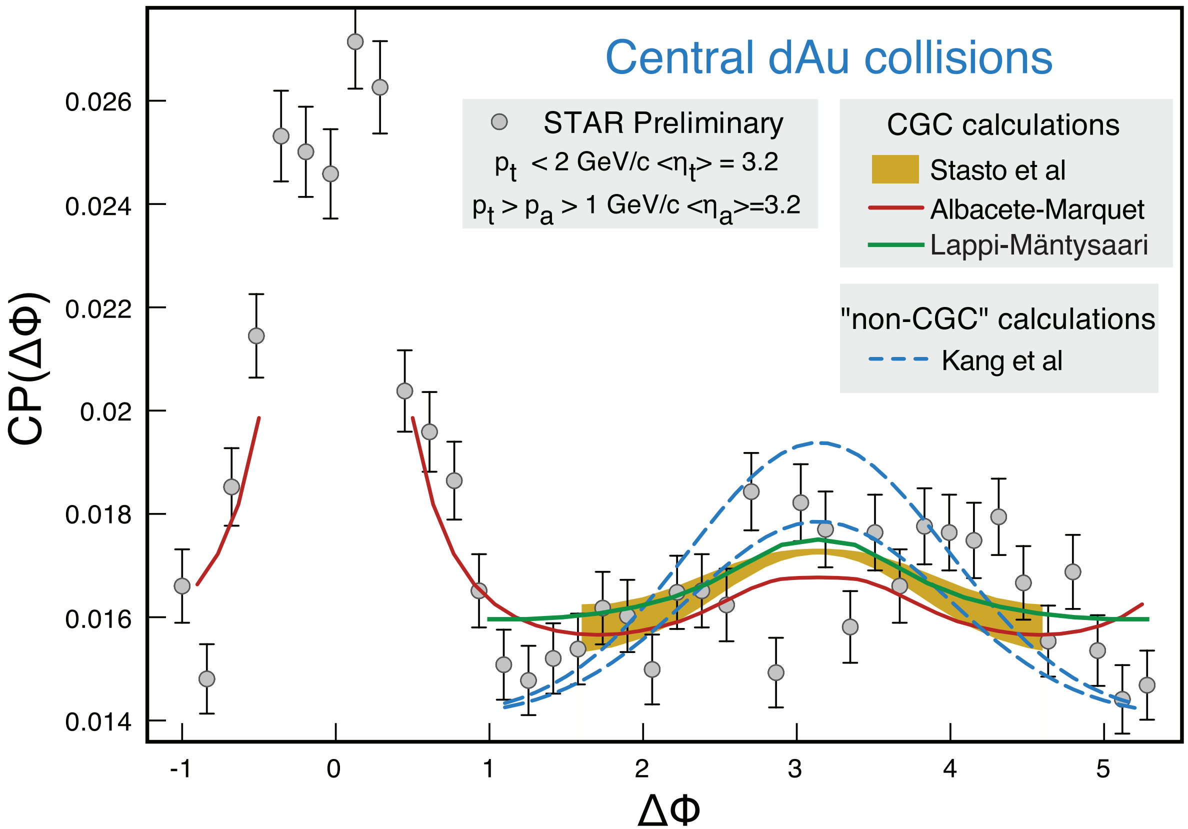


no absolute normalization due to exp. backgrounds

- CGC calculations complex but big improvements recently
  - CGC provides good description
- Away-side peak cannot be described in leading-twist collinear factorization framework
- Most striking evidence for saturation to-date

# p+A at LHC: Pinpointing the CGC?

- First long p+Pb run in Spring 2013
- Expectations:
  - No final state effects other than usual CNM effects
  - Absence of QGP “signatures”
  - Saturation effects visible in bulk matter (low-x, low-$p_T$), pronounced and clearly at forward rapidities

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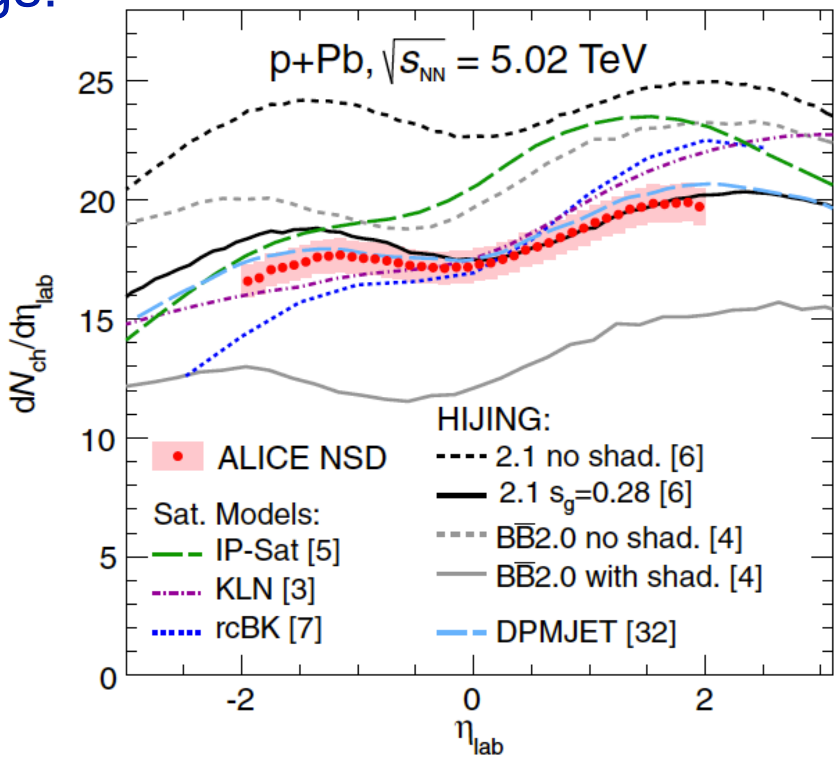


CGC models (mostly based on $k_T$ factorization) describe multiplicity in p+Pb quite well

Similar predictions at $\eta$ = 0

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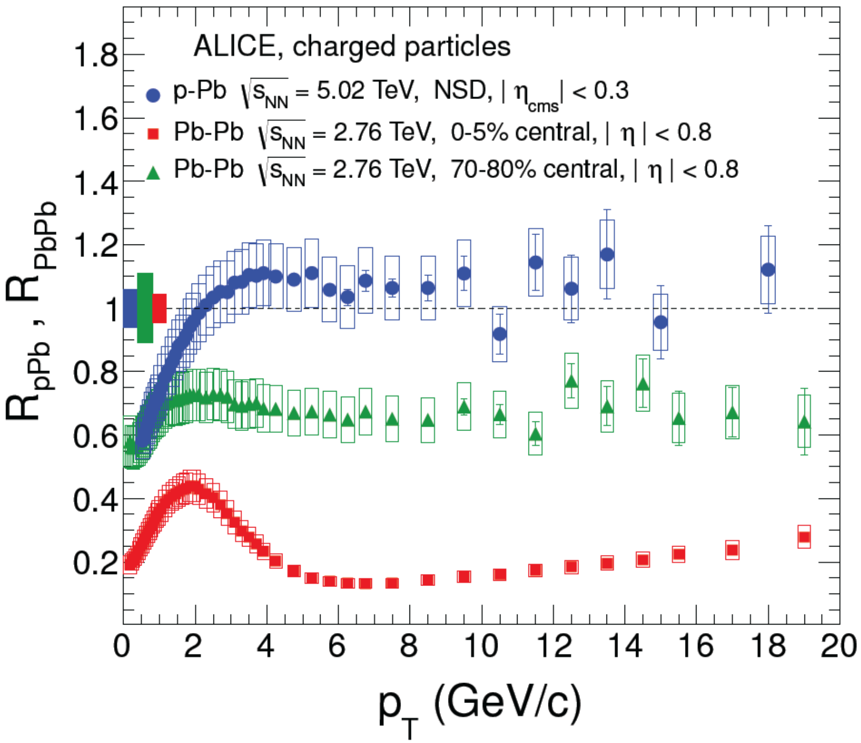


Classical QGP signature: Jet quenching

p+Pb: No suppression at high-$p_T$ observed for

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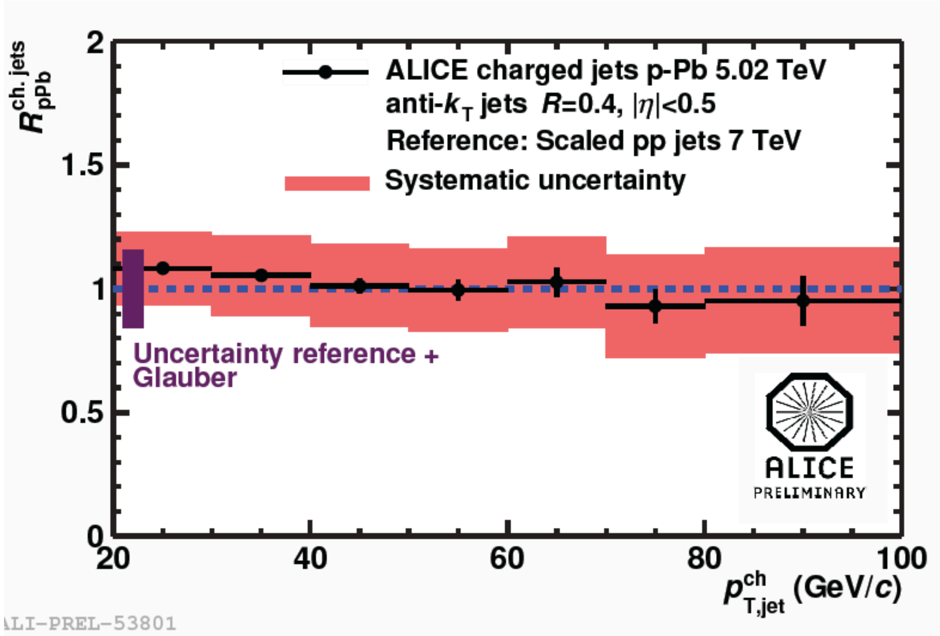


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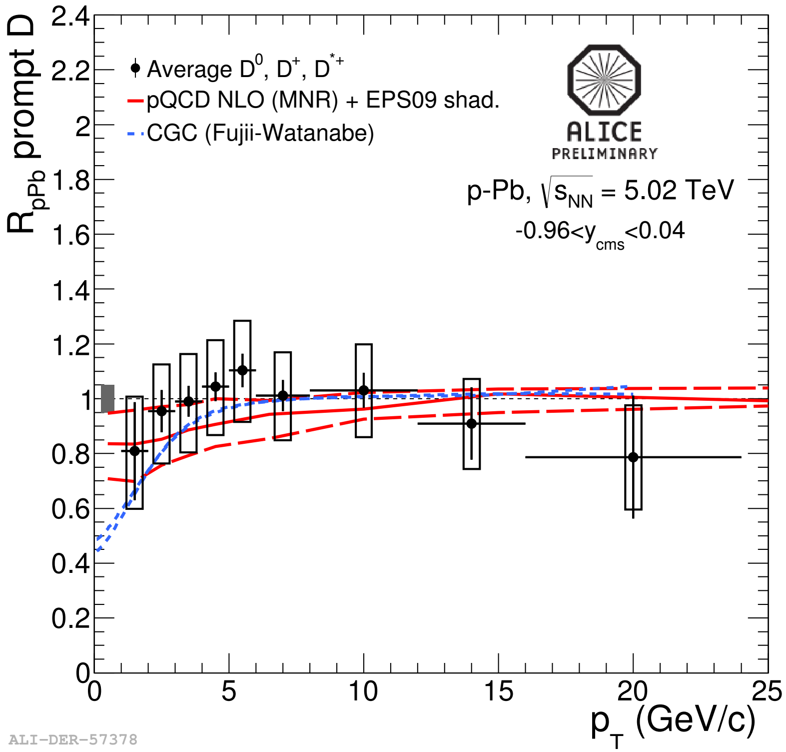


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p+Pb: No suppression at high-$p_T$ observed for

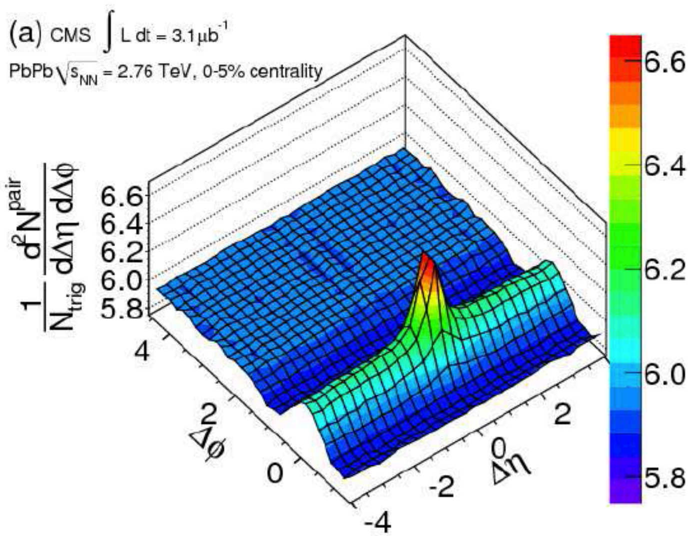
- Hadron Spectra
- Jets
- Heavy Flavor Mesons

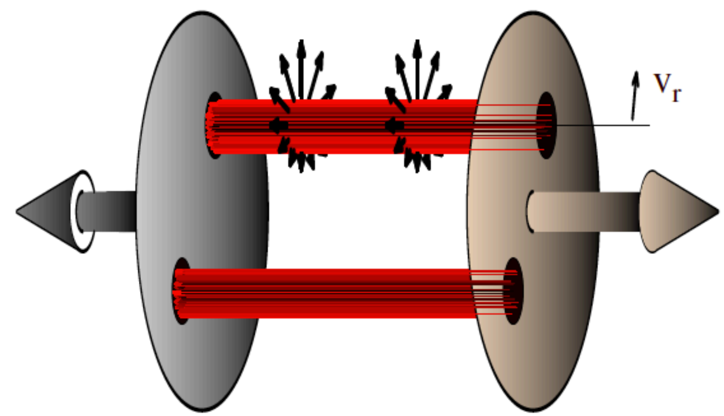
Absence of Final State Effects ?

# p+A at LHC: Along Came the Ridge

- Structure observed first in heavy-ion collisions
- Two-particle correlations at small relative azimuth Δφ~0, which extends over at least several units of relative rapidity Δη
- Particles separated by a large Δη are causally disconnected and cannot be correlated, unless they produced early

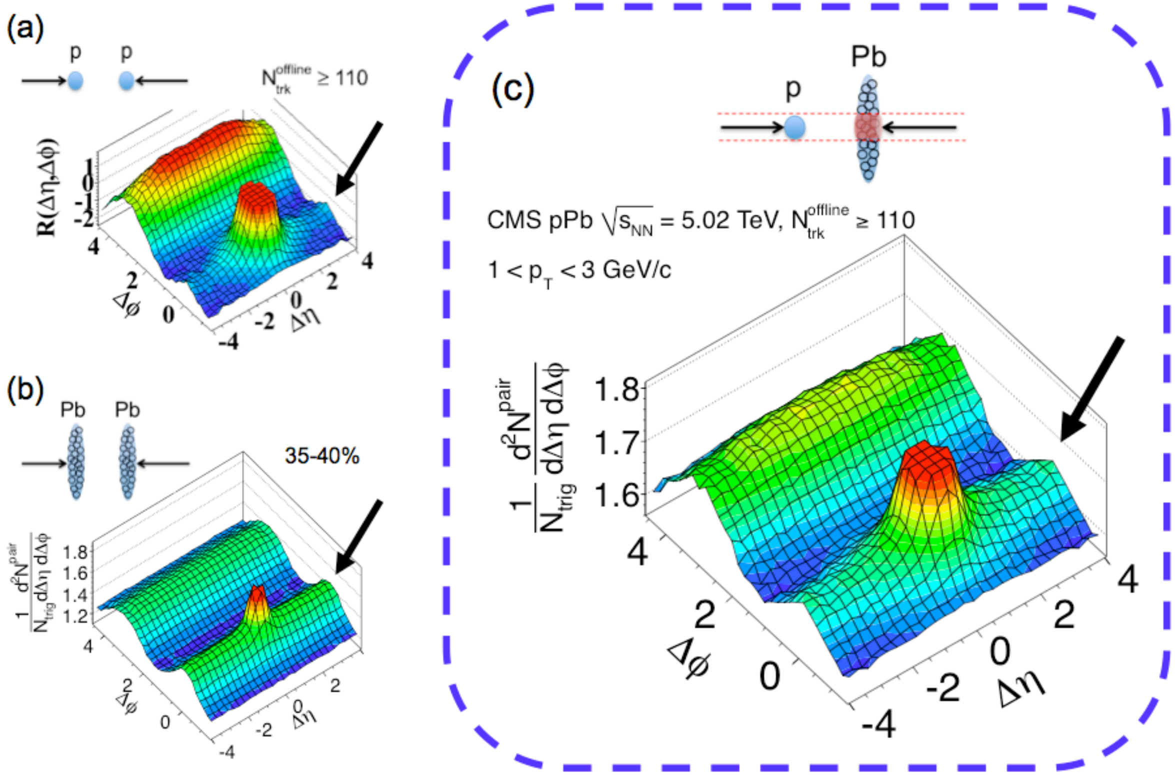
CMS: Pb-Pb



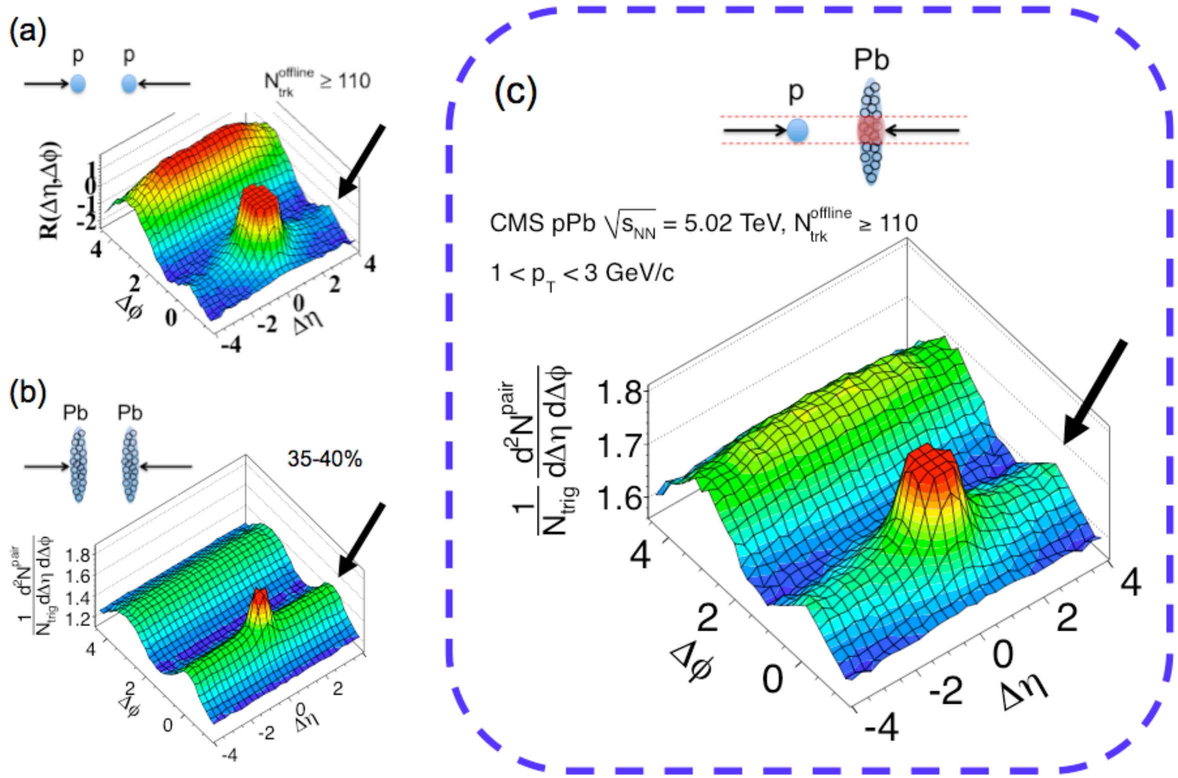

**Explanation:** Initial spatial distribution and fluctuations in hot QCD matter. Possible explanation in "Glasma" picture. (Hydrodynamics w/o initial spatial correlation does't create a ridge.)

# p+A at LHC: Along Came the Ridge




- Weaker ridge observed in pp in high multiplicity events
  - Consistent with strong-color-field picture
  - CGC explanation of ridge
    - e.g.: Dusling et al. Nucl.Phys. A836 (2010) 159-182

# p+A at LHC: Along Came the Ridge




- CMS & ALICE confirm substantial ridge structure in p-Pb
  - Absence of final state collective flow ⇒ explained by CGC momentum correlations same as in pp
  - Presence of collective final state effects ⇒ p+A ridge is result from hydrodynamic evolution

# p+A at LHC: Along Came the Flow

**p-Pb**

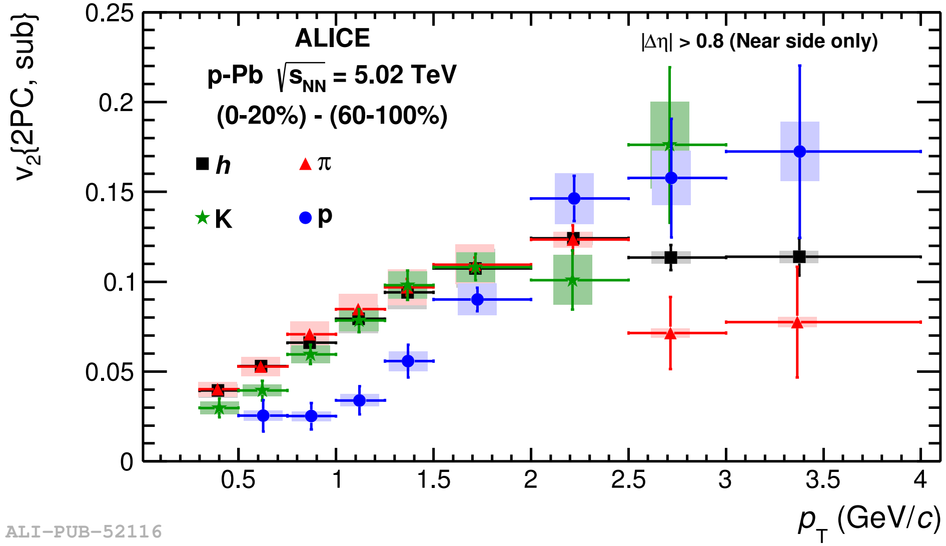
- Collective flow ($v_{2,3}$) observed
- Strength similar to Pb-Pb
- Suggestive of final-state collective effects

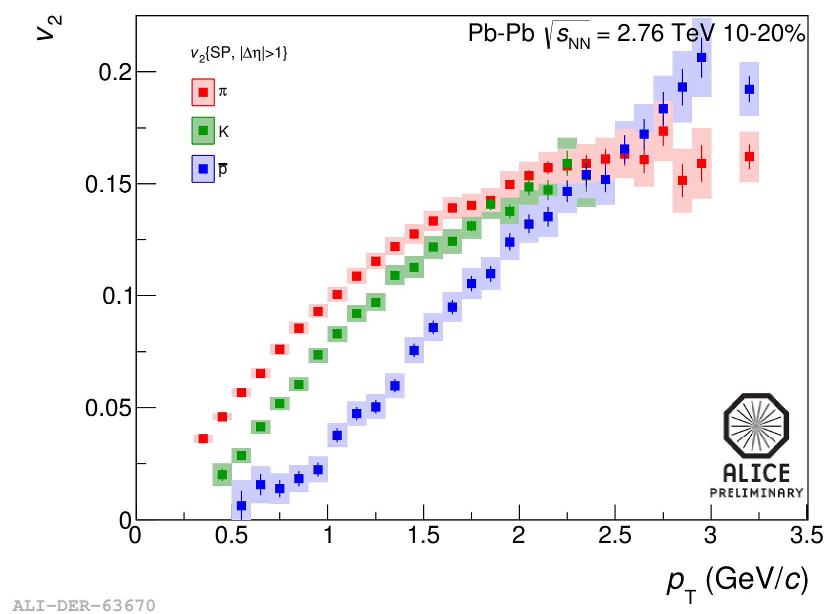
**RHIC d+Au**

- PHENIX observes flow ($v_2$) and ridge. Difference to STAR needs to be resolved.
    - Also d+A vs. p+A

**CGC**

- Latest calculations show that flow ($v_{2,3}$) is produced as well



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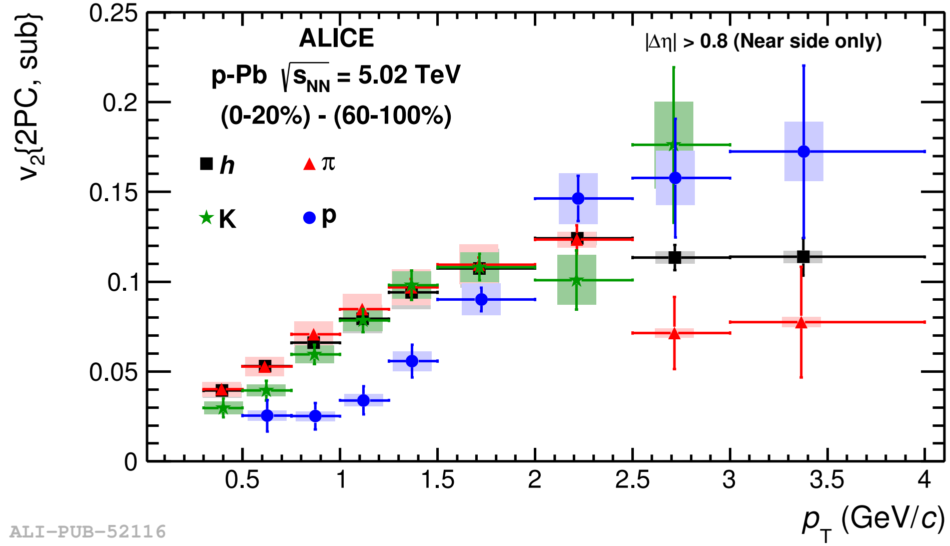
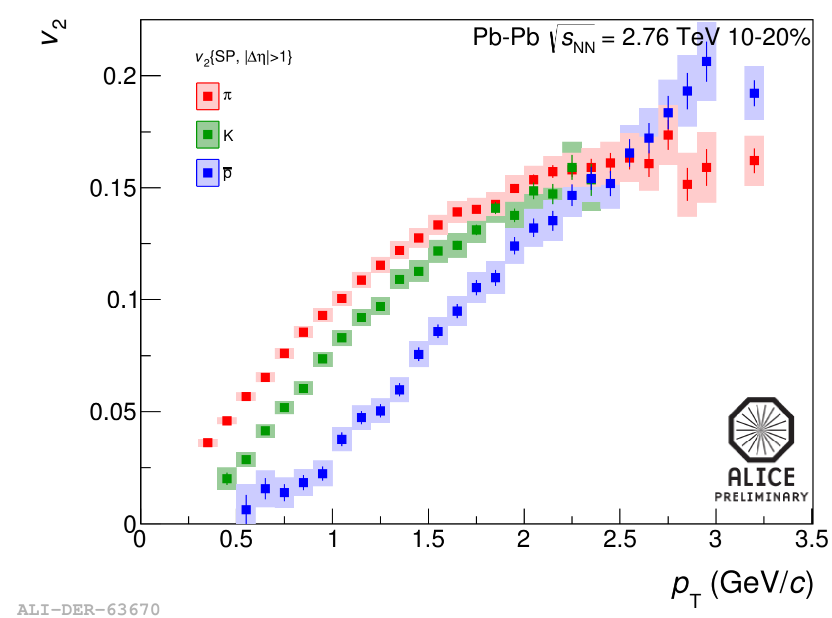
Still too soon to make definitive statement regarding CGC vs final-state collectivity



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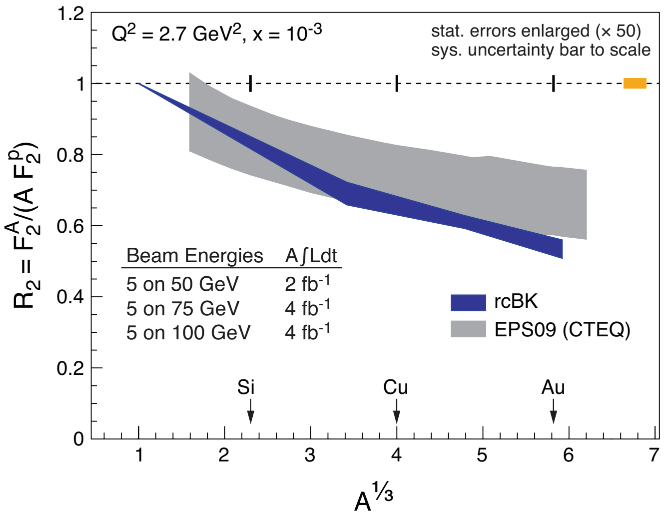
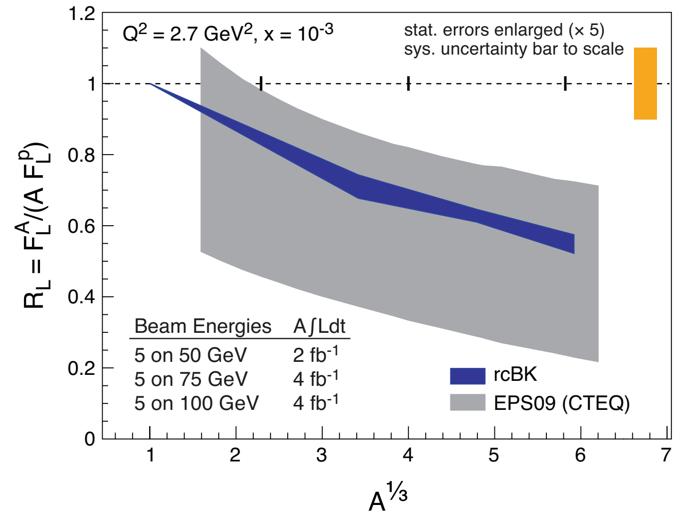
Despite LHC’s high energy and low-x reach, the EIC is not only relevant but absolutely essential to understanding QCD in the saturation regime. In fact the understanding of p+A and A+A results at LHC might depend on it.

# eA at EIC: Unique Key Measurements (I)

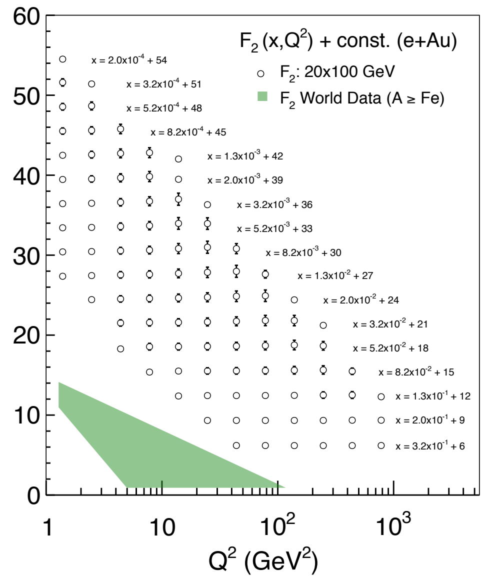
## Measurement of structure function $F_2$, $F_L$ and their characteristic A dependence at down to $x \sim 3\times10^{-4}$

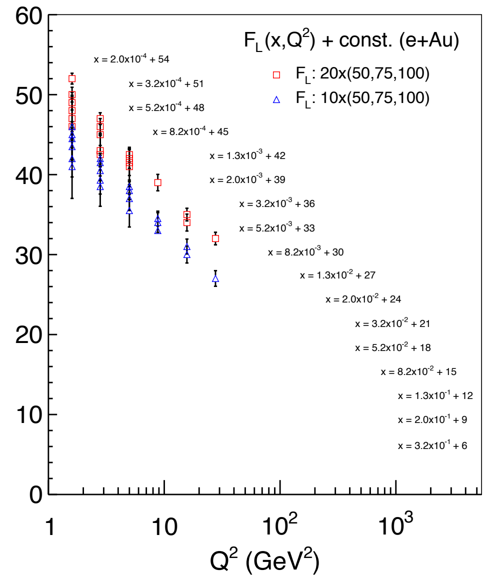
**EIC WP:**
Saturation predicts characteristic A dependence. Systematic error dominates



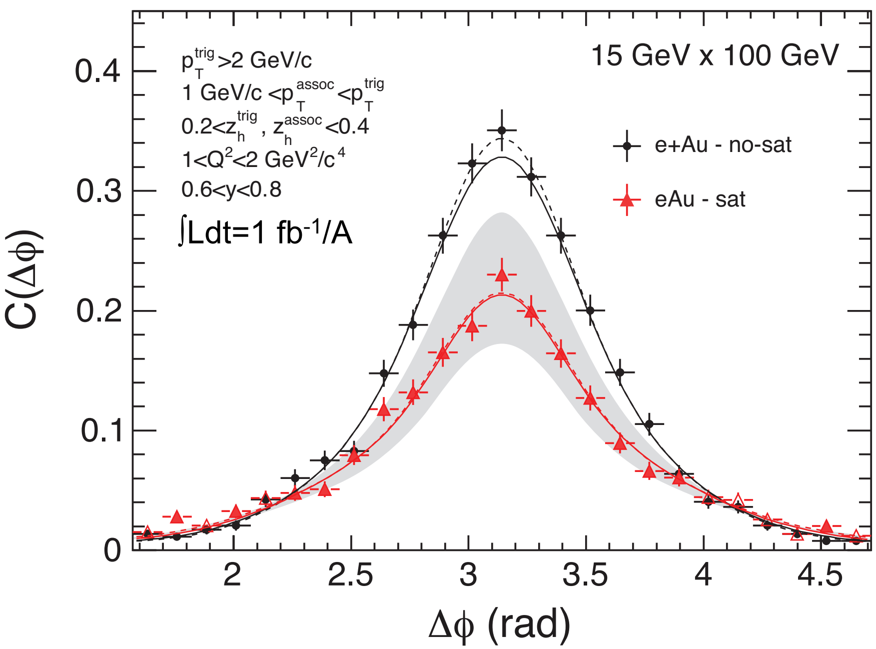

**New simulation:**
Kinematic reach and sys+stat errors for eRHIC

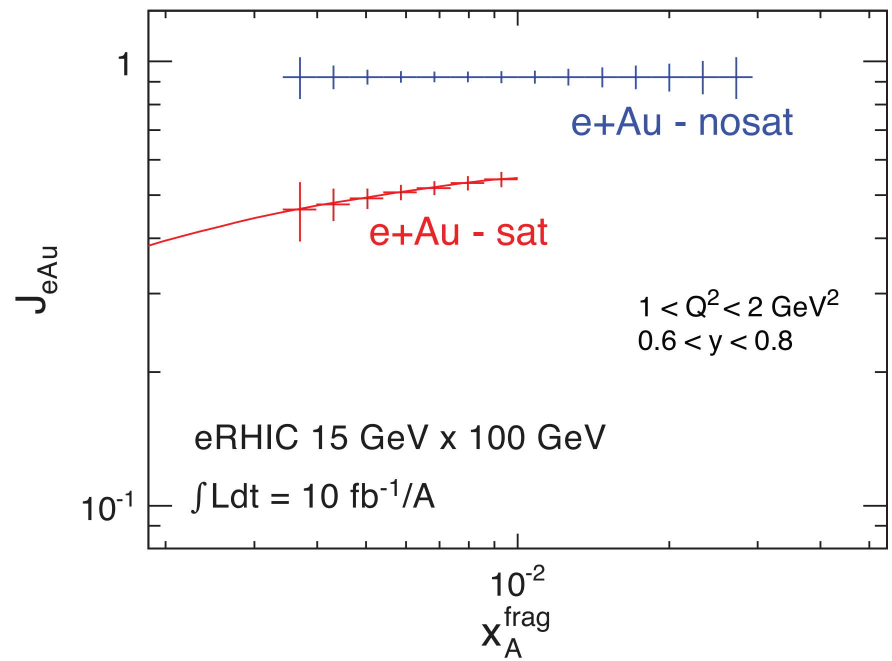


# eA at EIC: Unique Key Measurements (II)

Clear saturation/CGC signatures such as di-hadron correlations in a background free environment with access to the relevant kinematic variables



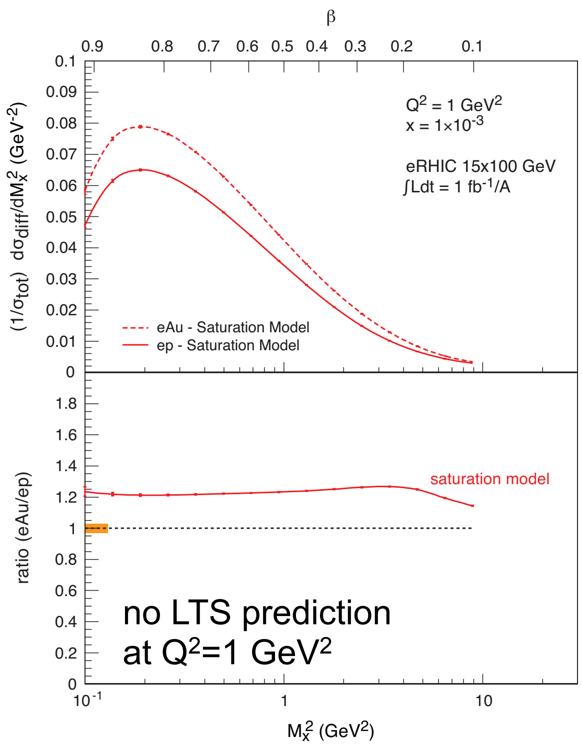



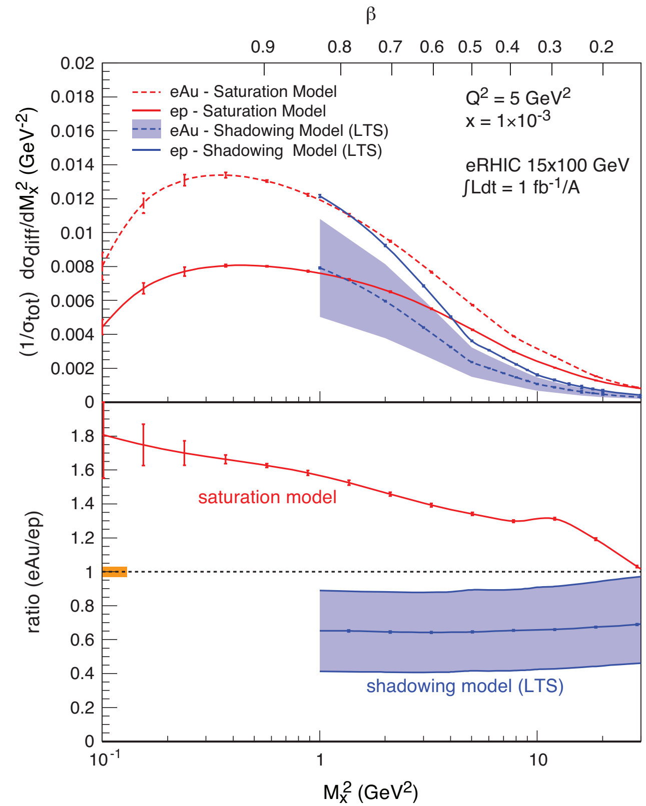

**New simulation:**

Now include Sudakov form factor to account for generated radiation through parton showers. Difference between sat and no-sat gets smaller but still significant. Include Kinematics and sys+stat errors for eRHIC.

# eA at EIC: Unique Key Measurements (III)

## Day-1 measurements that will give clear evidence for saturation such as differential $\sigma_{diffractive}/\sigma_{diffractive}$ ratio



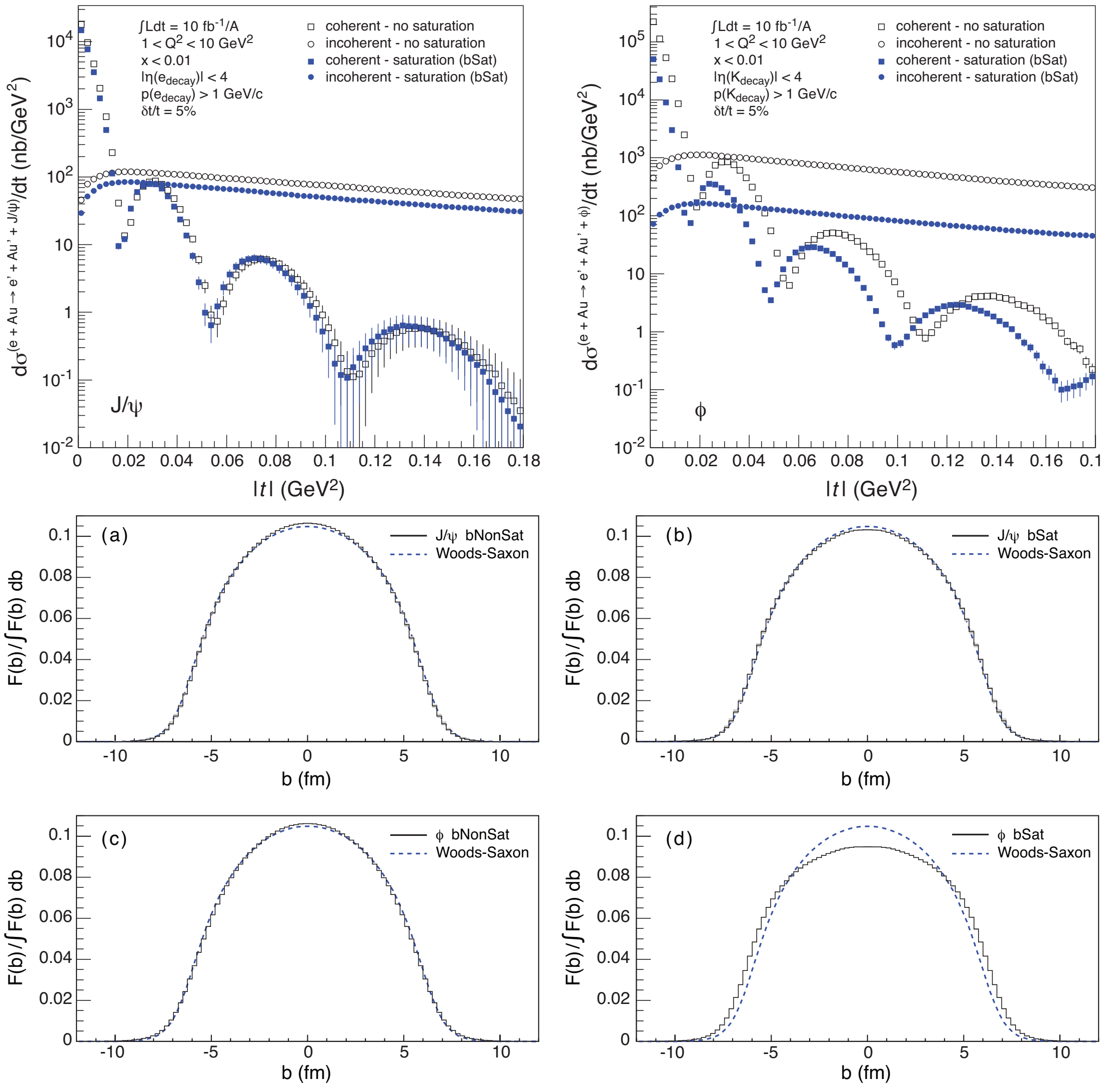




**New simulation:**

Saturation model calculations (Sartre event generator & analytic) now include $q\bar{q}g$ that affect the ratio at low β. Now confirm observation in arXiv: 0805.4809 of enhancement of double-ratio at large β and suppression at low β. Sat-simulations describe HERA results in ep.

# eA at EIC: Unique Key Measurements (IV)

## Measurement of diffractive vector meson production that allows to study the spatial gluon distribution in nuclei




**New studies:**
Proof that source distribution $F(b_T)$ can be obtained by Fourier transformation of $d\sigma/dt$.
Encouraging results: Already for $|t| < 0.1$ GeV$^2$ input distribution can be extracted with surprising precision (PRC C87, 024913)

*Critical:* Separation of coherent and incoherent part through detection of breakup *n* (ZDC) and optionally charged fragments in forward detectors (Roman Pots). Simulations show it works!

# Take Away Message

- The e+A program at an EIC is unprecedented, allowing the study of matter in a new regime where physics is not described by “ordinary” QCD
  - non-linear QCD/saturation/higher twist effects,
  - properties of glue (momentum & space-time)

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  - properties of glue (momentum & space-time)
- Exciting results at LHC and RHIC in p+A but also new complications in p+A studies at RHIC and LHC
  - collective effects indicate contribution from final state
  - key measurement of saturation not as clean-cut as anticipated
  - e+A at EIC might at the end be necesary to understand not only A+A but also p+A

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- Exciting results at LHC and RHIC in p+A but also new complications in p+A studies at RHIC and LHC
    - collective effects indicate contribution from final state
    - key measurement of saturation not as clean-cut as anticipated
    - e+A at EIC might at the end be necesary to understand not only A+A but also p+A
- Steady progress in studies of key measurements in e+A